Fermi National Accelerator Laboratory

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Electrical and Mechanical Design Report of the Muon Toroids for the Beamline to the Muon Laboratory

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CONTENTS

1. SUMMARY

This report describes two large steel toroids used to remove beam halo for experiment 665.

One toroid is 88 inch diameter and 30 feet long. The other is 120 inch diameter and 20 feet long. Both have a 7 inch diameter center hole for passage of the beam and the excitation windings. The assembled hybrid coil has water-cooled conductors in the center hole and cables on the outside. This permits the use of one piece steel plates through which the center core is inserted after assembly of the toroid steel. These toroids have advantages over conventional toroids in many aspects. The main ones being its reduced power consumption, simplicity of machining and assembly, and lower coil costs. Estimates of the induction and a simple method to buck the remnant magnetic field are included. The bucking method does not completely degauss all the toroid steel.

2. MECHANICAL DESIGN AND ASSEMBLY OF THE TOROID STEEL AND COIL

The toroid steel is made up of individual steel plate sections (See Figure 1). These plate sections are stacked face-to-face on a support frame (See Figure 2). The upstream toroid steel dimensions are approximately 88 inch diameter and 30 feet long made up of 17 plate sections. The downstream toroid steel dimensions are approximately 120 inch diameter and twenty 20 feet long made up of 13 steel plate sections.

There are four (4) - 2 1/2 inch diameter stainless steel screws set on a brass pad for vertical adjustment of the steel plate sections. Horizontal adjustment is obtained by pulling the brackets on the steel frame rails. Hilman rollers were placed under both sides of the steel plate support arms for horizontal moves. Small horizontal moves were obtained by sliding on the brass pads.

There is a 7 inch diameter opening in the steel center at the beam line for the coil center core and beam passage. The coil center core (See Figure 3) consists of 32 insulated water-cooled copper conductors mounted to an aluminum pipe. The coil center core assembly was prefabricated at the magnet factory. The coil center core conductors are cooled with a continuous flow of LCW water. The outer conductors (See Figure 3) consist of 128 insulated 2/0 AWG air-cooled cables. Each coil turn consists of one water-cooled center conductor connected to 4 parallel cables which form the outside return to the next center conductor.

The installation of the toroid steel and its coil are as follows:

1. Set, survey and grout in support frame (See Figure 2)

2. Place, survey and set individual toroid plate sections

3. Place the prefabricated coil center core (See Figure 3) into the toroid steel assembly.

4. Bend the center conductor ends up and attach the outer cables to the coil center core conductors.

5. Install the LCW water-cooling system for the center coil core conductors.

6. Connect main power leads.

3. MAGNETIC PROPERTIES OF THE STEEL

The toroids are assembled from distressed steel plates and leftovers. Some steel was purchased to complete the steel assembly. It is obvious that the magnetic properties of these materials are not homogeneous. We therefore need to make some assumptions in order to calculate the required ampere turns for 15 KGauss excitation at 120" radius. Based on experience with similar steel, we will assume that the steel behaves like C1030, shown in Fig. 4. To produce 15 KG requires 44 Oersteds or 44x80 = 3520 ampere turns per meter. Thus a circular field of 15KG at 120" diameter can be estimated to need: $\pi \times 120 \times 2.54 \times 10^{-2} \times 3520 = 33706$AT of excitation. The B-H curves of 8 samples cut from various places of the toroid steel, at a later date, were measured. The results for 2 samples are shown in Fig. 5 through 10. Most samples are close to Fig. 5 through 7.

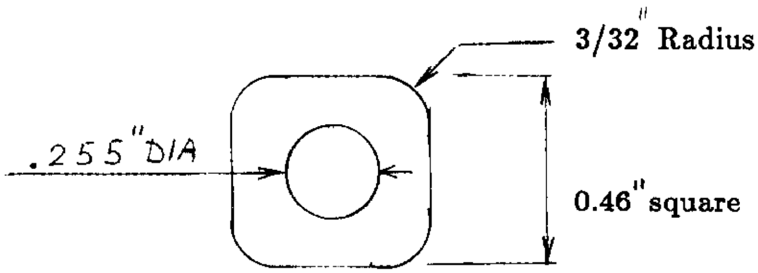
Not all curves are the same. It appears, from these measurements, that 55 Oersteds for 15KG is a better estimate for excitation calculations. The steel is in the non linear region at about 12 to 13 KG and starts to saturate at higher inductions. Practical coil design limitations allow only 25,600 ampere turns (33.4 Oersted at 120" dia.) yielding on average about 13 KG at 120" Dia. Sample 120-2 shows a very poor B-H curve and yields only about 9 KG at 33.4 Oersted. There is not much we can do about it. We will not use sample 120-2 for further estimates. All other samples are about the same.

4. COIL DESIGN

The conductors of the excitation coil have to pass through the 7" diameter center hole in the toroid steel. Physics requires that the coil volume in the center should leave about a 5.5" diameter free space for the beam. The available space for the coil volume is therefore low. Low coil volume can be achieved by using water-cooled copper bars mounted to an aluminum support pipe, which is then inserted through the center hole after assembly of the toroid steel. These copper conductors are connected in series with cables along the outside which completes the excitation windings.

High current density is used (~5200 A/inch^2) in the core conductors to get reasonable excitation. Both coils should be made similar so that they can be operated in series from one power supply. Booster copper, available from Fermi stock, is used for the center core conductors.

The properties of the booster copper are listed below:



Cross section	A	$= 0.153 \text{ inch}^2$
Weight	W	$= 0.59$ lbs/ft
Resistance at 20^oC	R_{20^oC}	$= 54 \times 10^{-6}\ \Omega/\text{ft}$
Resistance at 60^oC	R_{60^oC}	$= 63.4 \times 10^{-6}\ \Omega/\text{ft}$
Choose operating	I	$= 800A$
Current density	C	$= 5230 \text{ A/inch}^2$

For the return conductor use:

4 - 2/0 cables in parallel/turn.

2/0 data: $R_{25^oC} = 0.0811\ \ \Omega/1000'$

$R_{60^oC} = 0.0925\ \ \Omega/1000'$

Insulation : 600V, 90^oC

Ampacity : 285A single conductor, free air

The maximum number of booster copper bars we can fit inside the 7 inch Dia. center of the steel is 32.

Coil Design Data

		Toroid 88" Dia. 30 Ft Long	Toroid 120" Dia. 20 Ft Long	
Number of turns		32	32	
Current	A	800	800	
Each center conductor length est.	FT	33	23	
Total center conductor weight	LBS	623	435	
Total center conductor resistance 60^oC	Ω	$67x10^{-3}$	$46.7x10^{-3}$	
Total center conductor losses, 800A, 60^oC	KW	42.9	29.9	
Each center conductor cooling water inlet temp. max.	^oC	43	43	
Each center conductor cooling water outlet temperature	^oC	70	70	
Each center conductor overtemp. protection (klixon)	^oC	80±5	80±5	
Total center conductor required cooling at $\Delta T = 27^oC$	GPM	6	4.2	
Each center conductor inlet pressure	PSI	180	180	
Each center conductor outlet pressure	PSI	80	80	
Each center conductor ΔP	PSI	100	100	
Each center conductor flow	GPM	~3.5	~4.5	*
Total center conductor flow	GPM	~112	~144	*
Total center conductor restrict flow to	GPM	>7	>5	
Each return conductor length est.	FT	36	34	
Total return conductor resistance 60^oC	Ω	$27x10^{-3}$	$25.2x10^{-3}$	
Total return conductor losses	KW	17	16.1	
Total 2/0 cable length	FT	4600	4400	
Total coil resistance, 60^oC	Ω	$94x10^{-3}$	$72x10^{-3}$	
Total coil losses, 800A, 60^oC	KW	60	46	
Total coil voltage, 800A, 60^oC	V	75	57.5	
Operating ΔT, 800A	^oC	27 @(6GPM)	27@(4GPM)	
Total inductance at 800 A	H	1.2	1.1	

*Use flow restriction

Notes About Coil Design

1. Unrestricted flow is excessive. Feed the supply and return header with 3/8 diameter hose to restrict total water flow. Install all water inlets at one end and all water outlets at the other end of the center core assembly. This will prevent thermal stresses, which can bend the 30' or 20' long pipe.

2. Install one 80°C klixon at each centerconductor end for overtemperature protection and arbitrary inlet and outlet side selection.

3. Flows are calculated from flow tables.

4. The temperature rise is calculated from $\Delta T = \dfrac{KW \times 3.8}{GPM}$.

5. Building ventilation must be adequate to handle 33 KW losses to air.

6. The inductance is calculated from $L = \frac{N\Phi}{I}$, using startup from 0 remnant field. About 2/3 L applies when starting with a full remnant field, because of trapped remnant flux in the steel (See para. 6).

7. Coil Construction Advantages:

   7.1 The hybrid coil permits the use of one piece steel plates with a flame cut center hole. Expensive machining of mating steel plate surfaces is eliminated. The magnetic field per ampere turn is improved due to the elimination of the steel gap(s).

   7.2 The estimated cost of both hybrid coils was about 33% of the cost of all water-cooled coils. ($40,000 vs. $120,000 for two coils, in this case). The actual hybrid coil cost was $50,000 for both coils, installed, including labor and material.

   7.3 Coil operating power losses of the hybrid coil are about 60% of the all water-cooled coil. (Approximately 60 KW/coil vs. 95 KW/coil.) Power savings are approx. $17,000/coil operating year, when running continuously at full current.

   7.4 Field installation of the hybrid coil uses conventional construction equipment. Installation is a lot easier, especially in areas of limited working space.

   7.5 The tolerances of the outer steel dimensions are not critical for the assembly of this type of coil. Variations in length and diameter can easily be accommodated during field assembly because of the flexability in the outer cable turns.

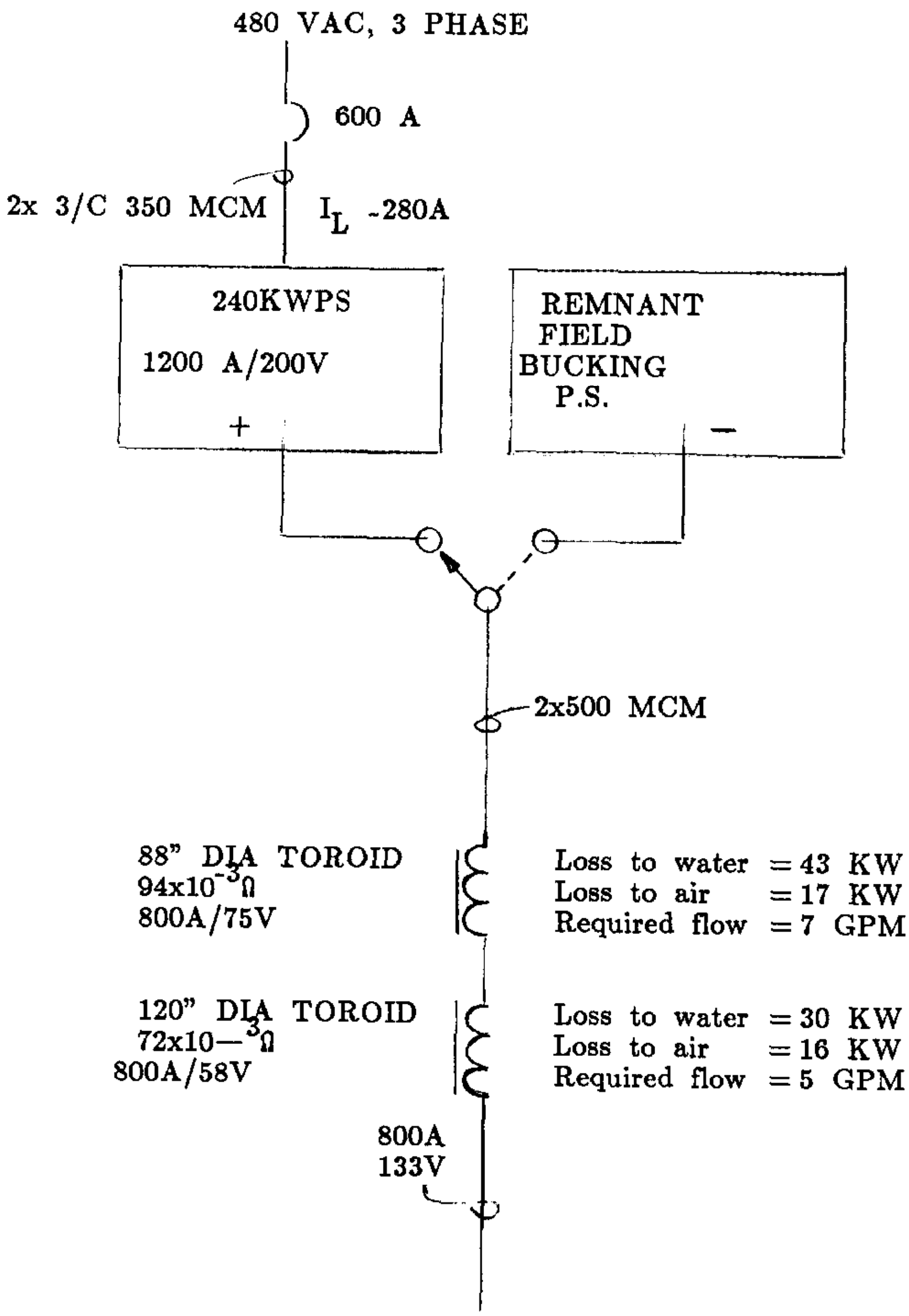
   7.6 The location of the coil power connections can be selected in the field.

   7.7 Water-cooling requirement is less because of the use of air-cooled cables. Losses to building air are higher.

   7.8 Damage to the outer winding can be easily repaired.

7.9 Elimination of a shorted turn, should it occur, is simple. The shorted turn can be removed from the circuit.

Both toroid coils are similar and operated in series from one power supply as summarized below:



The excited coil produces 25,600 AT at 800A. Fig. 11 shows the estimated toroid field as a function of the radius using BH curves from the measured samples. We find that the field (800A) is about 13 KG at 120" and increases to about 21 KG at 7". The field at the outer DIA area could be slightly (500 to 1000 G estimate) raised by surging the toroid current up to about 1200A and than backing down to 800A running current. It is estimated to take less than one minute to reach 1200A, with full power supply voltage, starting from zero.

6. A Method to Automatically Reduce the Remnant Magnetic Field

A substantial remnant will be left in the toroids after the current is turned off.

Fig. 12 and 13 show the expected remnant field as a function of the radius. It is desirable, for some physics experiments, to reduce the remnant field to zero or a low value. The steel can be degaussed by reversing the excitation current repeatedly, while reducing the current value gradually at every step, until it is zero. Precise current control around zero is required. System time constants are in the order of 10 sec. and degaussing could take up to one hour if we were to use the run power supply and a solid state reversing switch. A solid state reversing switch and controller need to be added to the existing installation for degaussing. Another problem is the precise control of the degaussing current at low (~1 amp) values, without any overshoot, after reversal startup. Controlled degaussing is not expected to work at low currents, when using the run power supply. It would be better to operate the run power supply in voltage regulate and use a series resistor at the low end. The resistor also reduces the current decay time constant. A better solution would be to use a smaller power supply, with a mechanical reversing switch and a series resistor at the low end. With this method, we would in essence, use the run power supply to degauss the toroids at the larger diameters, while the small power supply would degauss the area close to the center. Figs. 12 and 13 indicate the estimated current required to buck the remnant field at a certain radius. It also gives us a feel for the fact that small currents create large fields in the center, but do not have much effect at larger diameters. Degaussing must be started at about 600A to take care of the larger diameters. 600A will operate the outer steel in the non linear induction region, which is required for successful degaussing. Reducing the current 15% at every step is expected to give good degaussing over the entire volume of the toroid. This method of degaussing is effective, but time consuming. Again, no equipment has been installed for this method of degaussing.

If we compromise, and accept that the remnant field only needs to be zero at a selected diameter, than we can automatically switch on a remnant field bucking power supply upon shutdown of the run power supply. The estimated amount of bucking current for each region is plotted in Fig. 12 and Fig. 13. The previous excitation history affects the amount of required bucking current. The curves have been estimated from an average sample B-H curve. They are not very accurate, because there is not enough detail in the measured sample curves, however they give a good feel for what is needed. It can be estimated from these curves, that we need about 1A of bucking current for each inch diameter of the steel, to drive the field to zero at that diameter. A few search loops of small wire have been installed through one steel plate. This loop encloses a small range of diameters. The enclosed integrated flux change of the search loop is zero for matched values of I_{run} to I_{buck} (Ref. 1).

This can be checked by connecting the induced voltage of the search loop to an integrator from startup to I_{run} through I_{buck}

The total integrated voltage is zero, when I_{buck} cancels all the remnant flux left by I_{run}. We would not know if there was already any remnant flux in the steel at the start of the test, but only know if we made a change in the value of the remnant field compared to the starting value. This type of check may therefore not have much merit unless we start out with a degaussed toroid.

Figs. 14 and 15 show the electrical connection and controls for the toroid run and bucking power supply as installed. The load (toroids) is automatically transferred to the bucking power supply via a solid state transfer switch and controls. This scheme was chosen, because it is only a slight modification of our standard solid state reversing switch and control. The current from the bucking power supply can be set from remote, but after we gain some experience the control can be made such that the bucking supply comes automatically on at a preset level within 2 minutes after shutdown of the run power supply. It is important that the run current decays below the holding current of the transfer switch SCR's, before the bucking supply is allowed to start. This required decay time was measured to be about 75 seconds. Thus the minimum required deadtime between "RUN and "BUCK ON" has to be at least 75 seconds. The transfer controller uses therefore a 120 second (standard is 60 sec) transfer time for each transfer.
The calculated current decay time constant of the load is

$$\frac{L}{R} = \frac{2.3}{0.166} = 13.9 \text{ sec.}$$

for zero remnant flux. The trapped remnant flux makes the real curent decay time constant shorter and the ratio of the time constants indicates how large a percentage of the flux remains in the iron as remnant flux.

Let τ_o be the calculated time constant for zero remnant flux and τ_r the measured time constant with remnant flux.

Than we can write:

$$\tau_o = \frac{L_o}{R_{Load}} = \frac{N\phi_o}{IR_{Load}}$$

$$\tau_r = \frac{L_r}{R_{Load}} = \frac{N\phi_r}{IR_{Load}}$$

$$\frac{\tau_o}{\tau_r} = \frac{\phi_o}{\phi_r}$$

$$\tau_o = 13.9 \text{ sec (calculated)}$$

$$\tau_r = 6.4 \text{ sec (measured)}$$

τ_o is required to remove 100% of the flux

τ_r is required to remove $\frac{6.4}{13.9}$ 100 = 46% of the flux

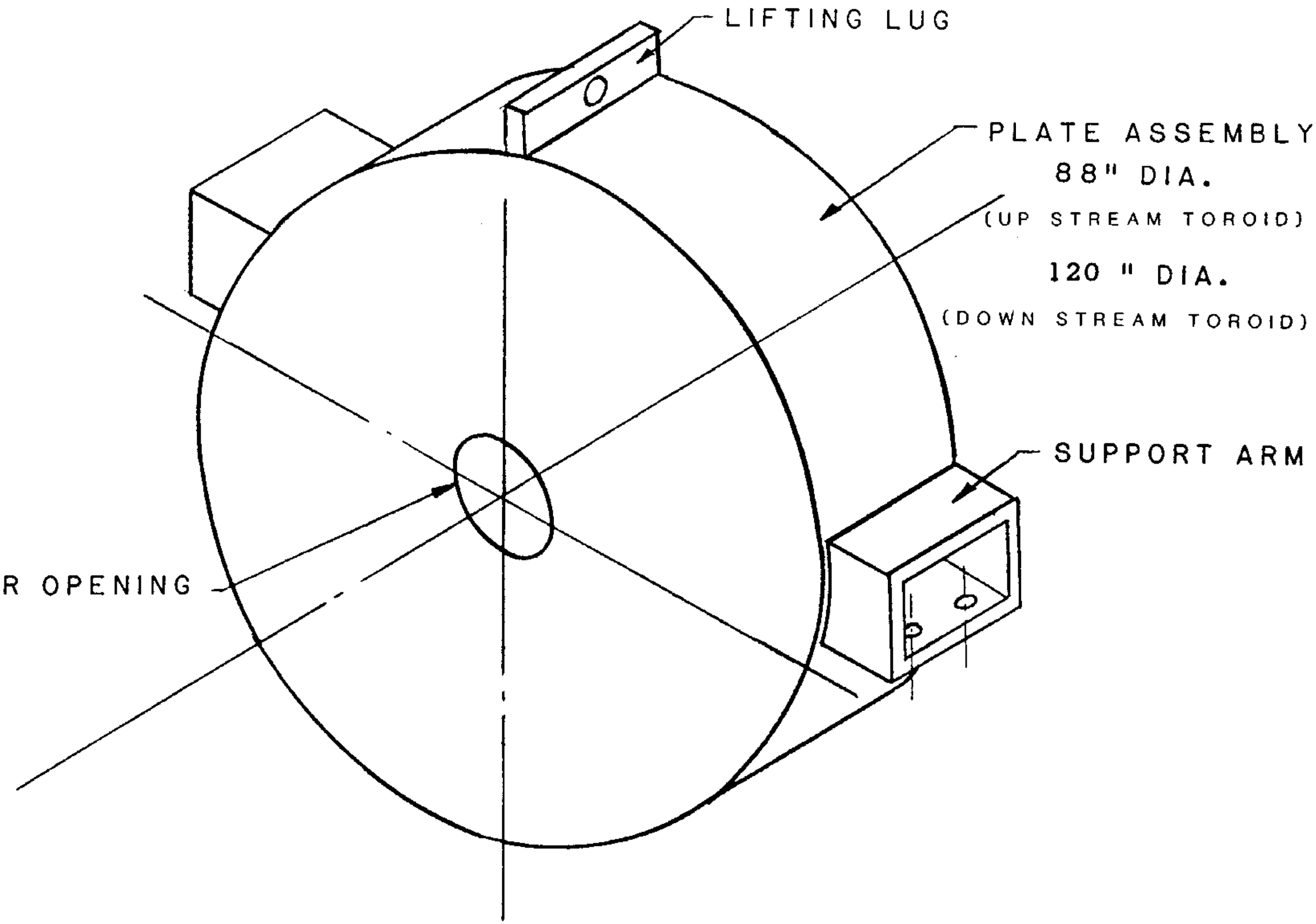
while leaving the rest as trapped remnant flux in the steel.

This indicates that about 54% of the flux remains in the iron as remnant flux upon shutdown of the run supply. This would indicate an average remnant field (see fig. 11, 12, 13) of about 7.5 K gauss, which is higher than indicated by the measured curves. Nevertheless it is an interesting exercise and it indicates that a substantial amount of remnant flux remains in the steel.

ATV

REFERENCES

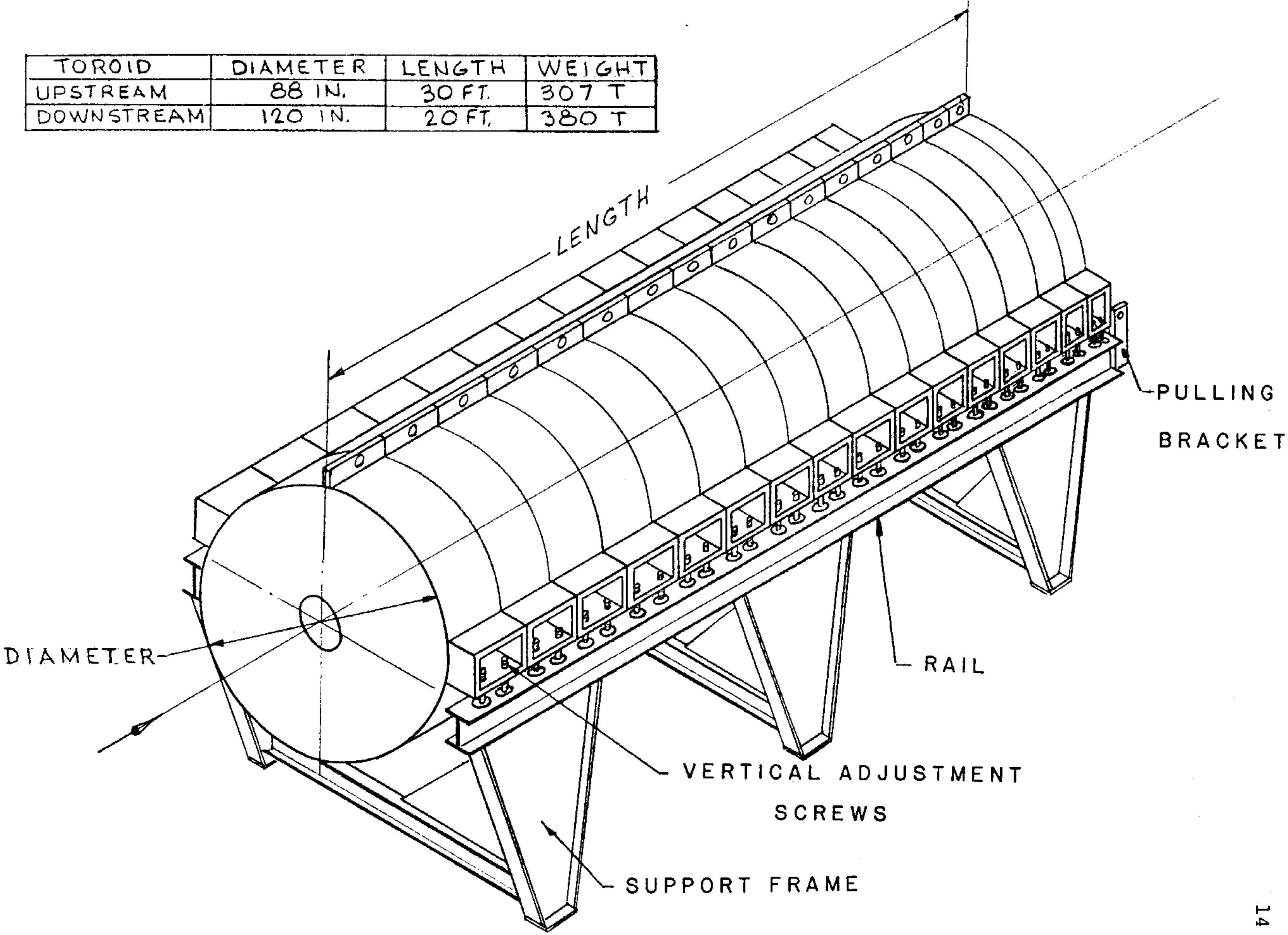
1. Meson West Beamline Spoiler Magnets Electrical Design and Test Report, TM #1432, A.T. Visser, Nov. 25, 1986, #9204.00



STEEL PLATE SECTION

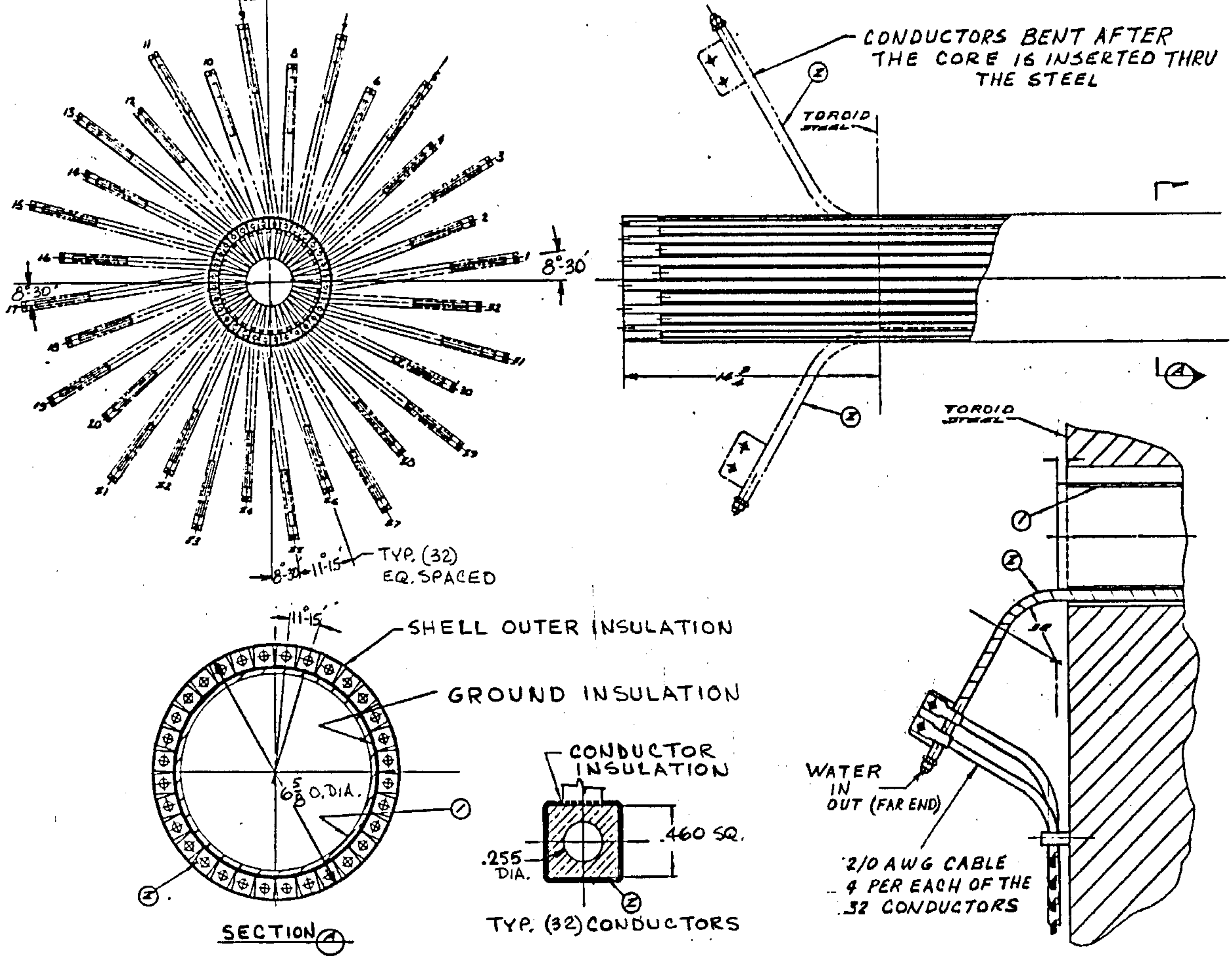
FIGURE 1

TOROID	DIAMETER	LENGTH	WEIGHT
UPSTREAM	88 IN.	30 FT.	307 T
DOWNSTREAM	120 IN.	20 FT.	380 T



TOROID STEEL ASSEMBLY

FIGURE 2



COIL CENTER CORE

FIGURE 3

USS HOT ROLLED LOW CARBON STEEL PLATES
C1030 — OVER .250 INCHES
DC MAGNETIZATION

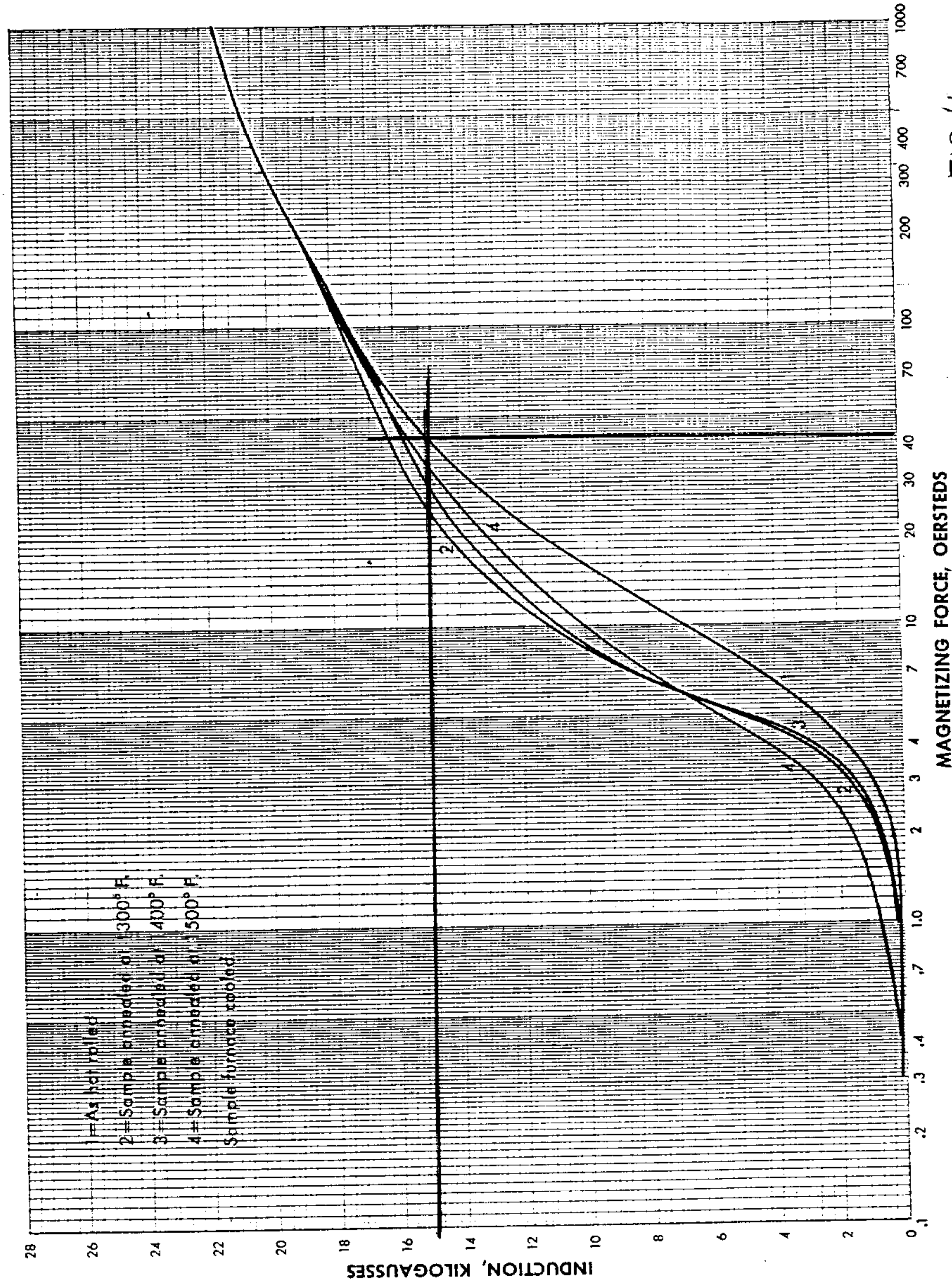


FIG 4

Test Conditions: Lengthwise samples tested in Fahy Permeameter.

STL. DRWG. REF. 9204.150 MD-202605

FERMILAB ENGINEERING NOTE	SECTION: RD/MECH.	PROJECT: N.M.D Toroid MUON BEAM	SERIAL-CATEGORY: SK-101785-1-B	PAGE: 1 OF 3
SUBJECT: MAGNETIC PROPERTY OF TEST SAMPLE #120-1 FROM 120" OCT. STEEL (ARNOLD ENG. CO. P.O. 900070)	NAME: A. SKRABOLY, A. VISSER	DATE: 10-17-85	REVISION DATE:	

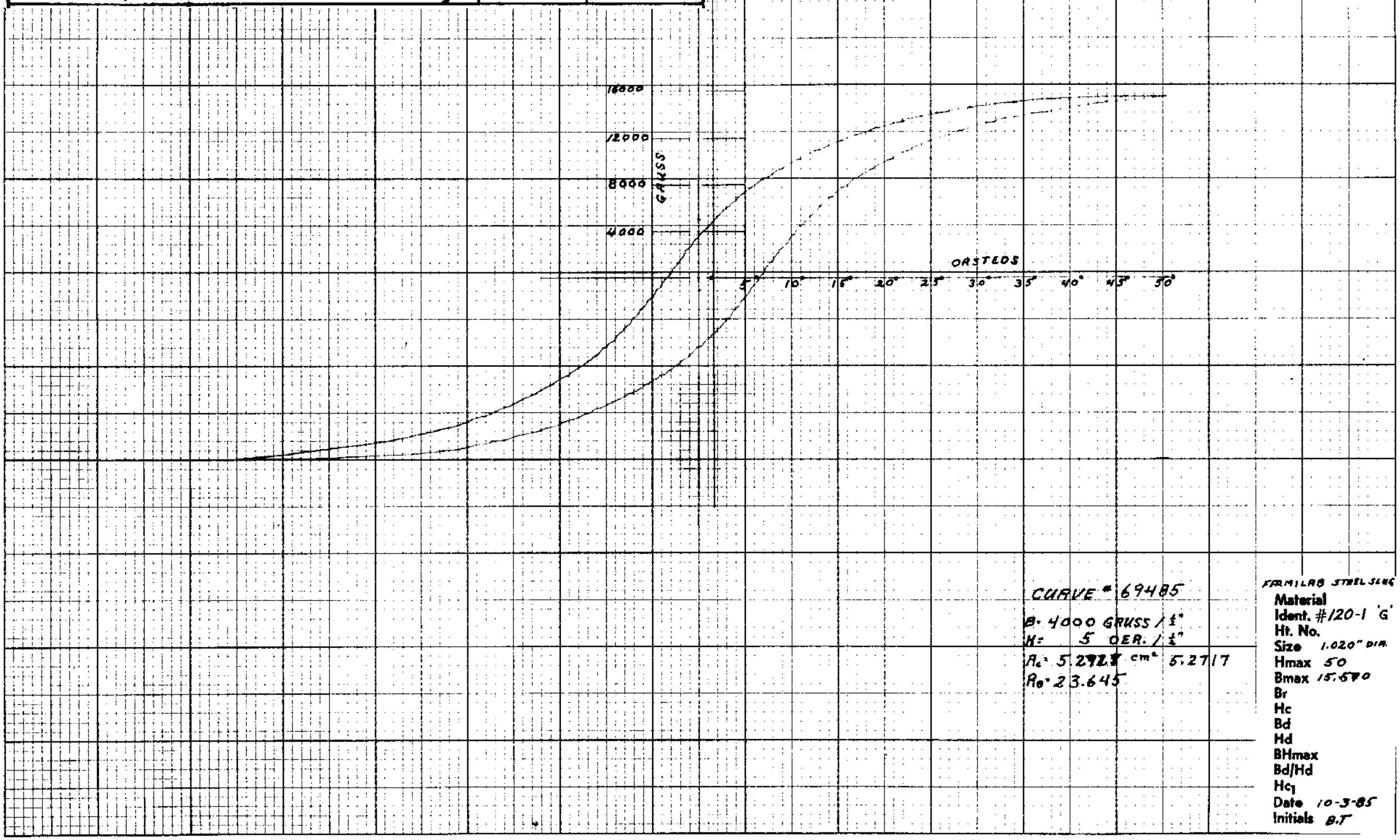


FIG 5

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
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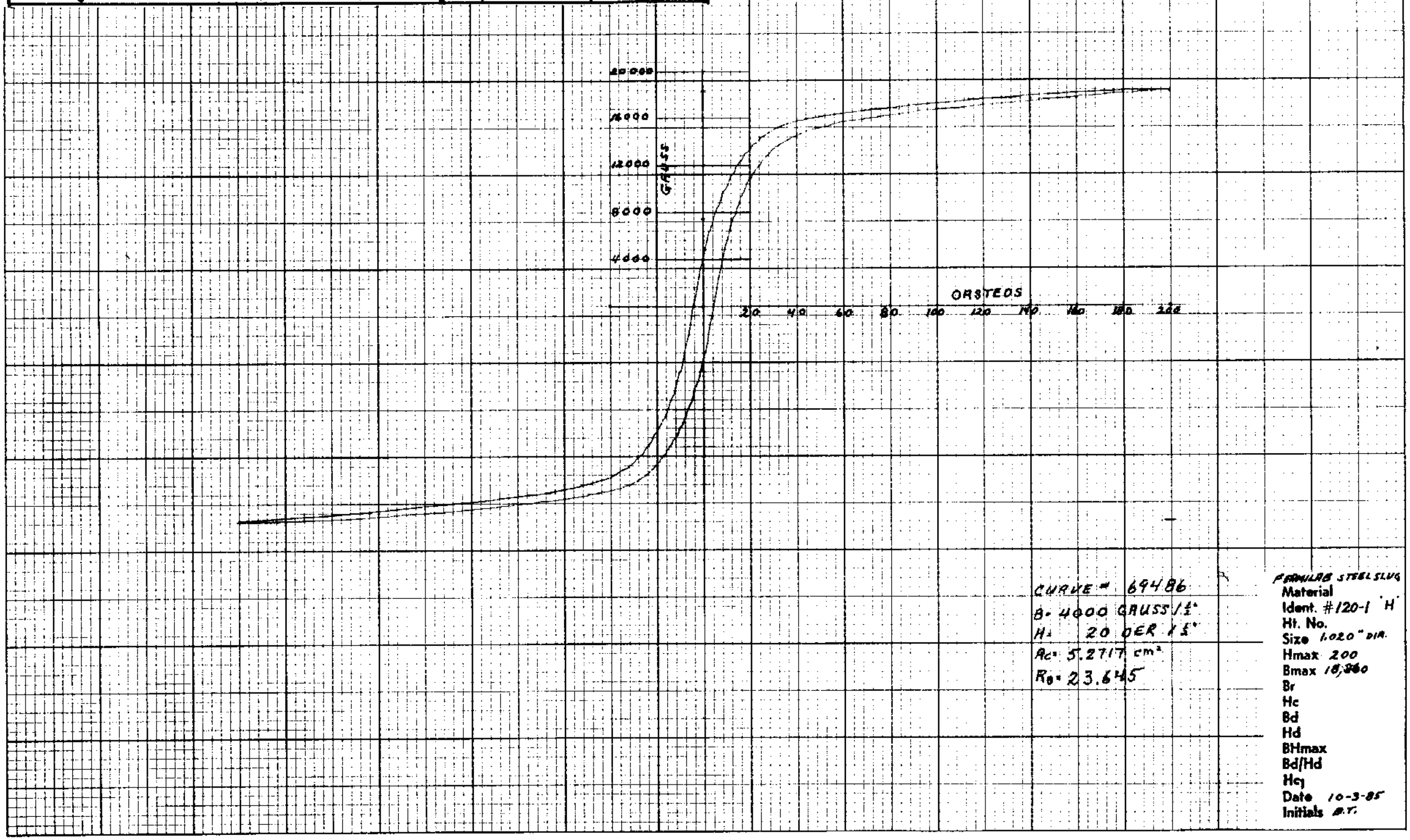
SUBJECT: MAGNETIC PROPERTY OF TEST SAMPLE #120-1 FROM 120 OCT. STEEL (ARNOLD ENG. CO. P.O. 900070)

NAME: A. SKRABOLY, A. VISSER

DATE: 10-17-85

REVISION DATE:



120-1

FIG 6

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120 I

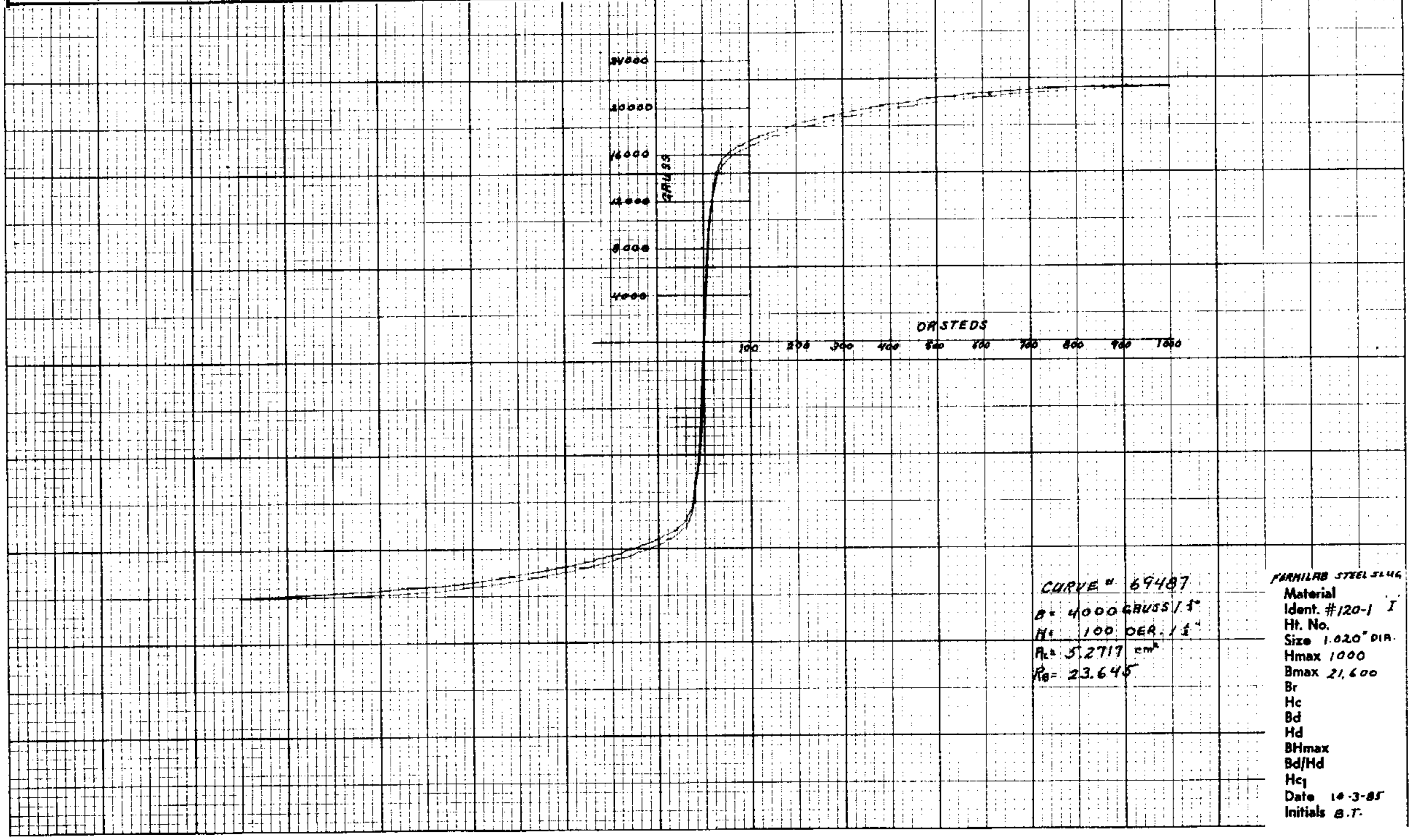
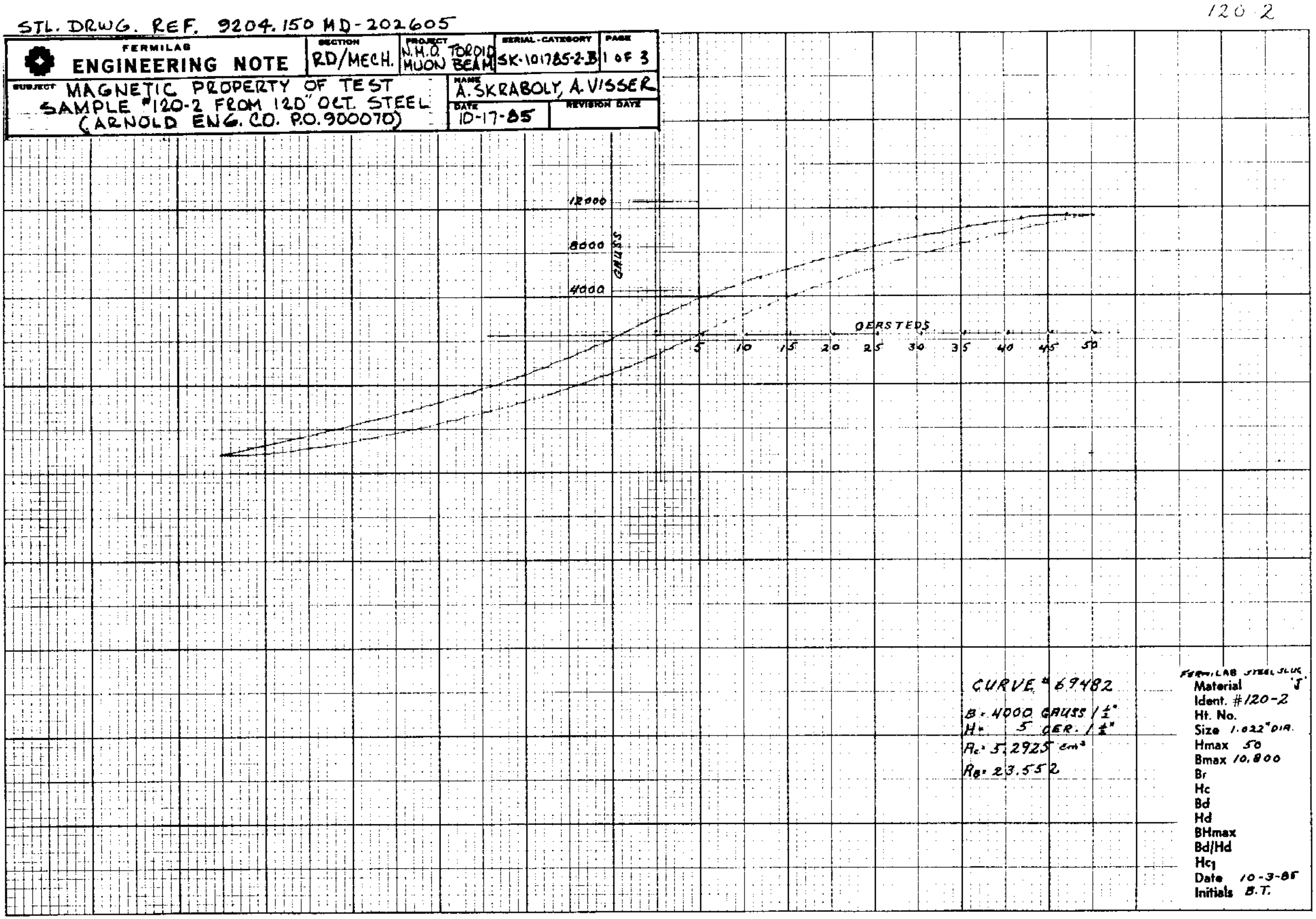


FIG 7


120-2
STL. DRWG. REF. 9204.150 MD-202605
FERMILAB
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SECTION RD/MECH.
PROJECT N.M.O. TOROID MUON BEAM
SERIAL-CATEGORY SK-101785-2-B
PAGE 1 OF 3
SUBJECT MAGNETIC PROPERTY OF TEST SAMPLE #120-2 FROM 120" OCT. STEEL (ARNOLD ENG. CO. P.O. 900070)
NAME A. SKRABOLY, A. VISSER
DATE 10-17-85
REVISION DATE
12000
8000
4000
GAUSS
OERSTEDS
5
10
15
20
25
30
35
40
45
50
CURVE # 69482
B = 4000 GAUSS / 1/2"
H = 5 OER. / 1/2"
A_c = 5.2925 cm^2
A_B = 23.552
FERMILAB STEEL SLUG
Material 'J'
Ident. #120-2
Ht. No.
Size 1.022" DIA.
Hmax 50
Bmax 10,800
Br
Hc
Bd
Hd
BHmax
Bd/Hd
Hc_1
Date 10-3-85
Initials B.T.

FIG 8

FERMILAB ENGINEERING NOTE	SECTION RD/MECH	PROJECT N.M.O. TOROID MUON BEAM	SERIAL-CATEGORY SK-101785-2B	PAGE 2 OF 3
SUBJECT MAGNETIC PROPERTY OF TEST SAMPLE # 120-2 FROM 120" OCT. STEEL (ARNOLD ENG. CO. P.O. 900070)		NAME A. SKRABOLY, A. VISSER	DATE 10-17-85	REVISION DATE

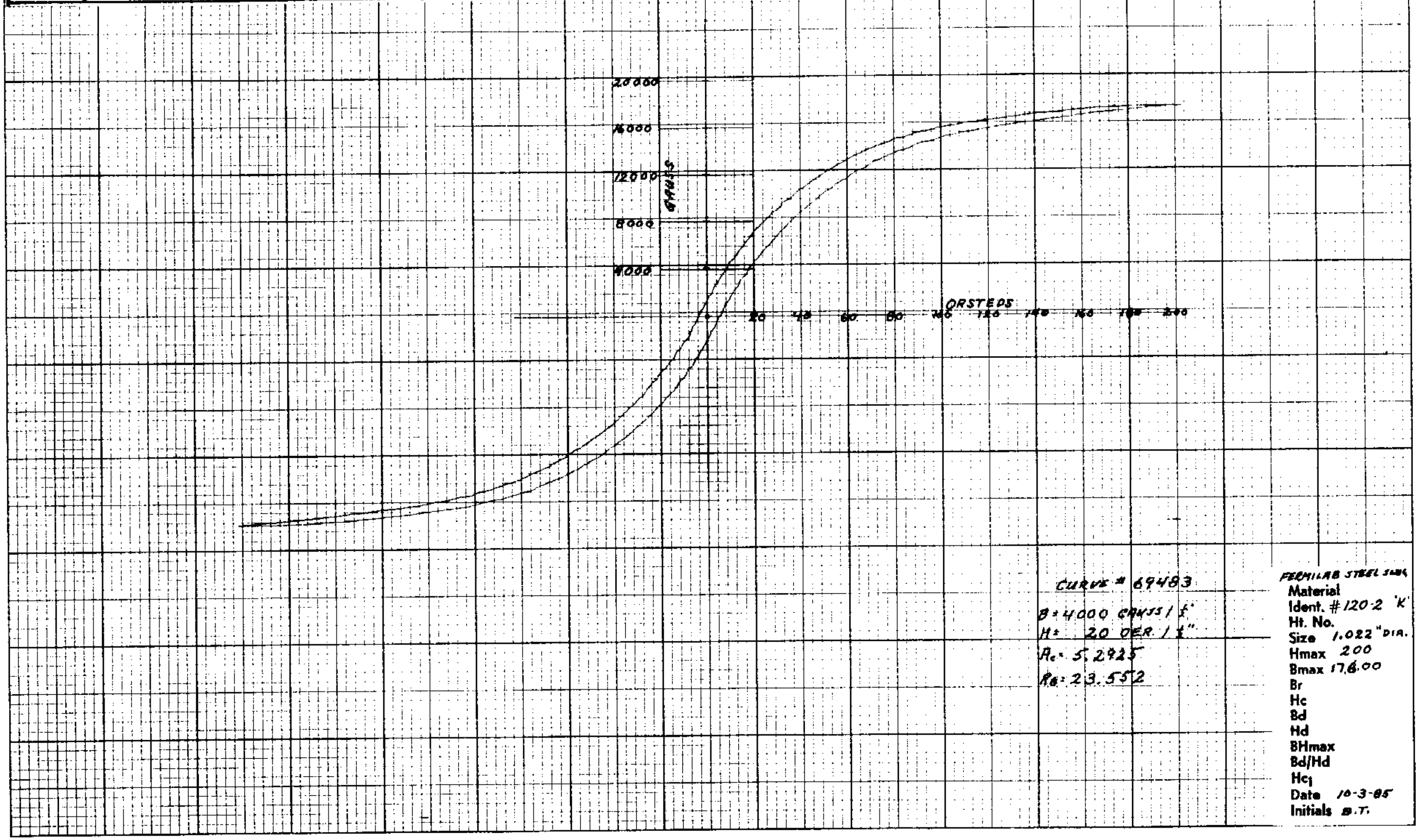

FIG 9

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ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
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SUBJECT	NAME
MAGNETIC PROPERTY OF TEST SAMPLE # 120-2 FROM 120" OCT. STEEL (ARNOLD ENG. CO. P.O. 900070)	A. SKRABOLY, A. VISSER
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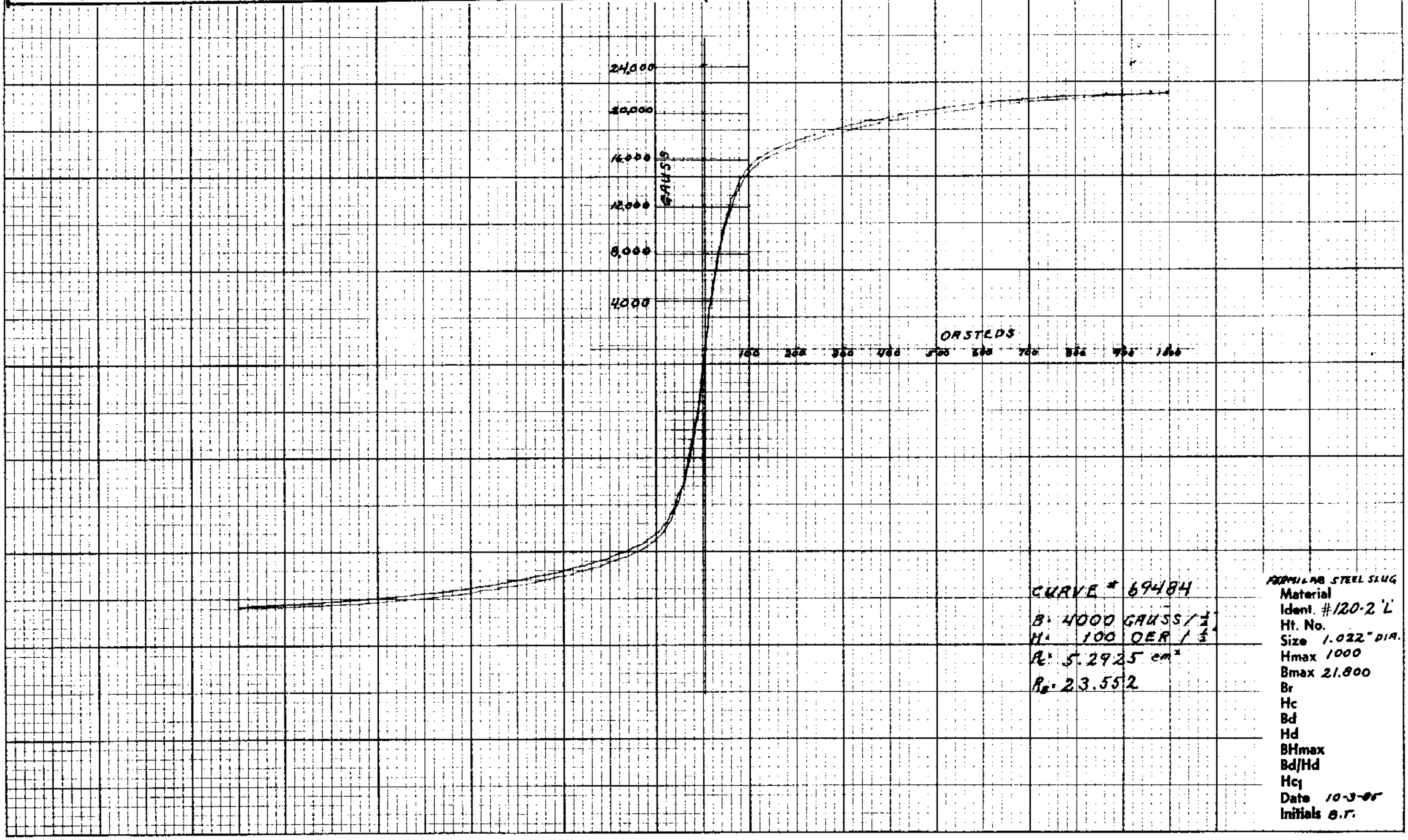

FIG 10

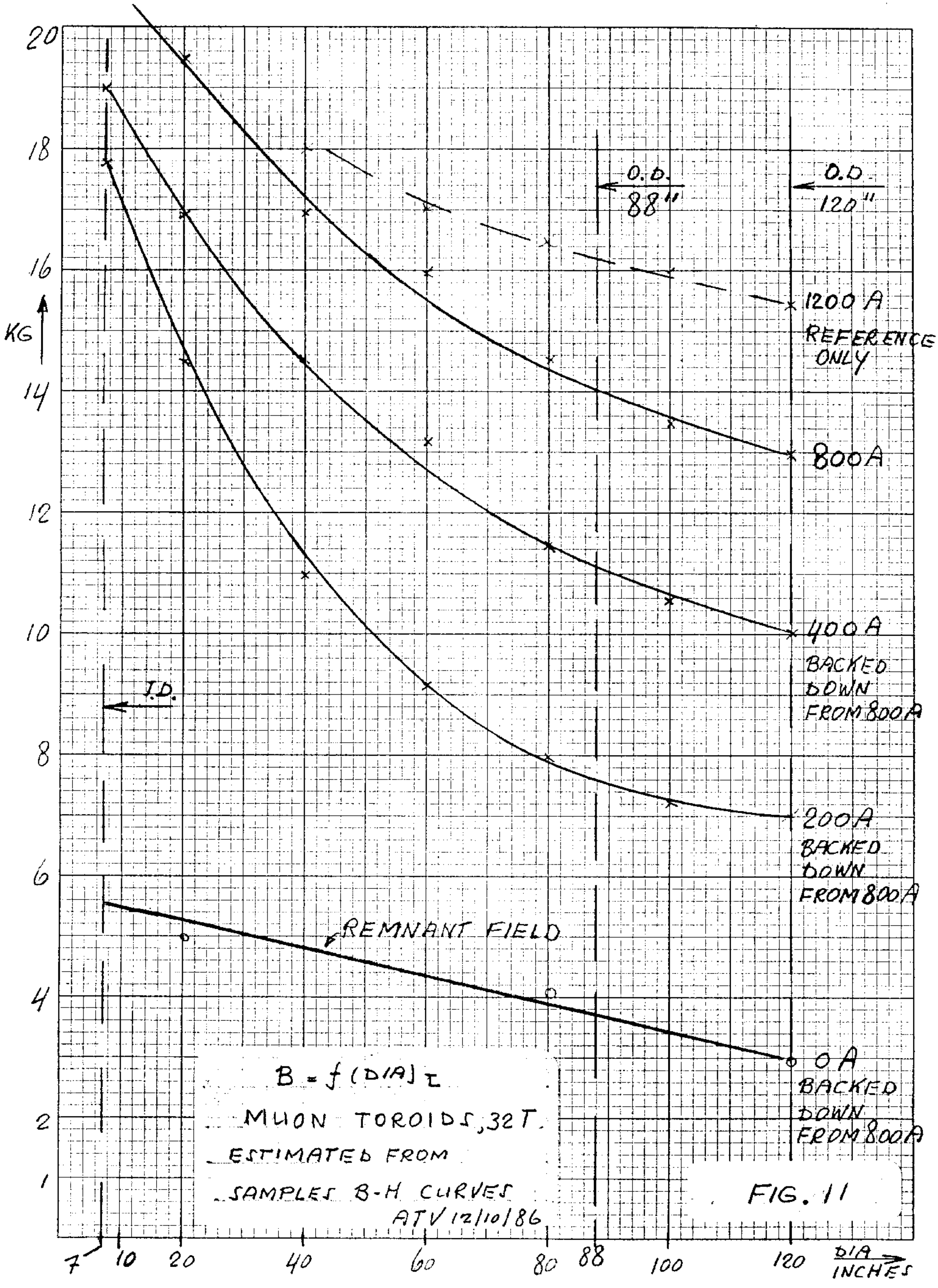
20
18
16
14
12
10
8
6
4
2
1
KG
O.D. 88"
O.D. 120"
1200 A
REFERENCE ONLY
800 A
400 A
BACKED DOWN FROM 800 A
200 A
BACKED DOWN FROM 800 A
I.D.
REMNANT FIELD
0 A
BACKED DOWN FROM 800 A
B = f (DIA) I
MUON TOROIDS, 32 T.
ESTIMATED FROM
SAMPLES B-H CURVES
ATV 12/10/86
7
10
20
40
60
80
88
100
120
DIA INCHES

FIG. 11

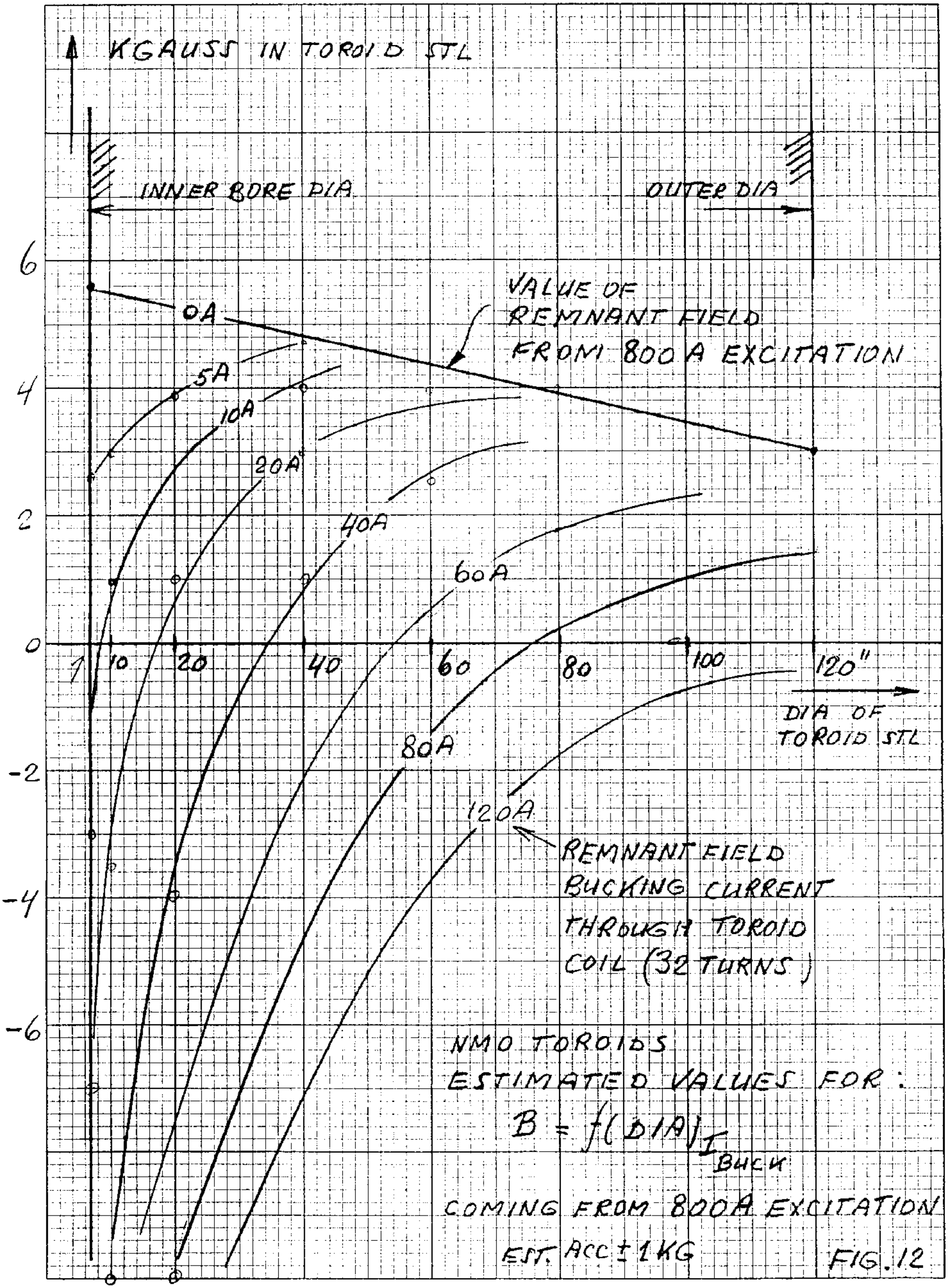

FIG. 12

A.T. VISSER 12/14/86

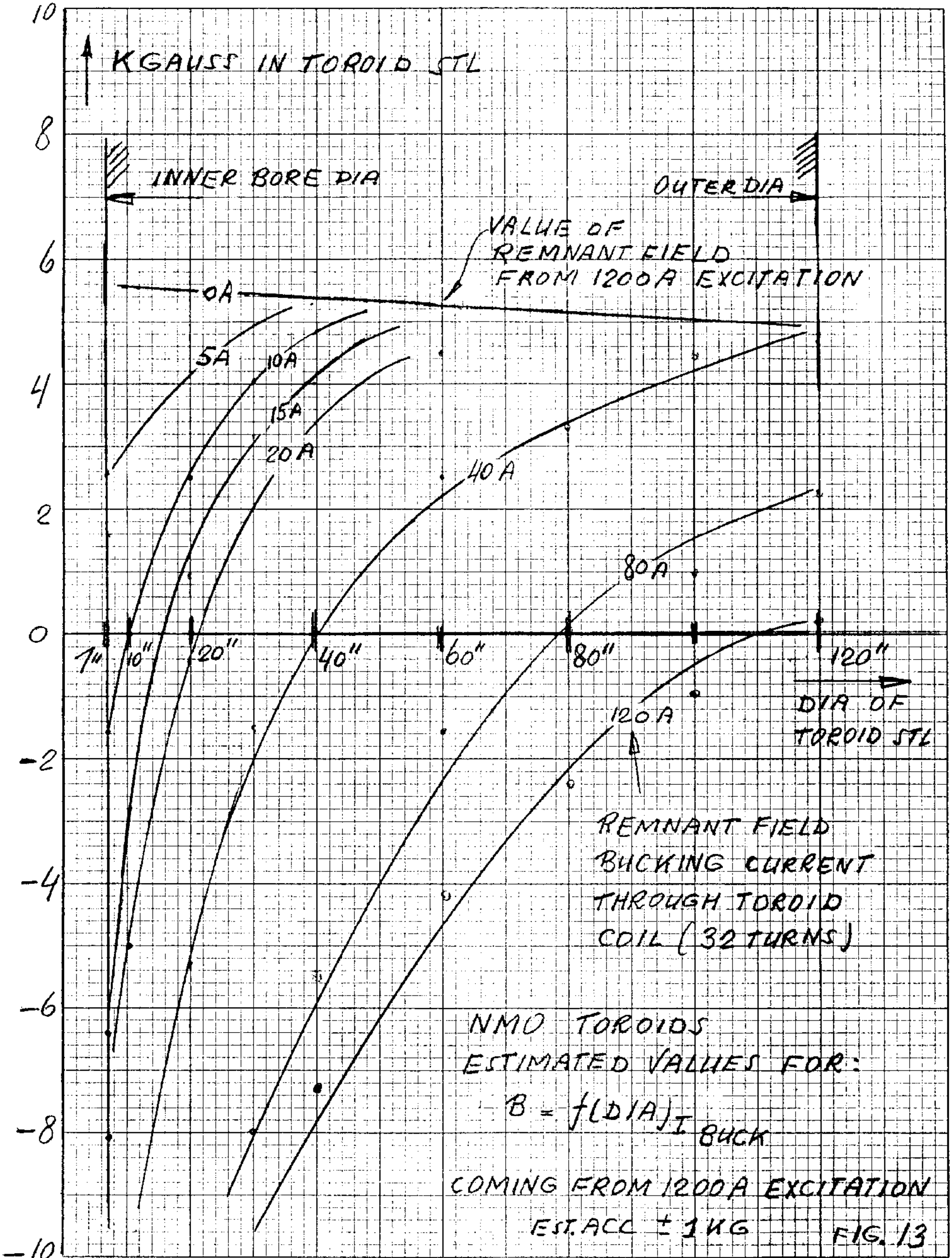

FIG. 13

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FERMILAB **ENGINEERING NOTE**

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
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NAME: A.T. VISSER

DATE: 11/12/86 REVISION DATE:

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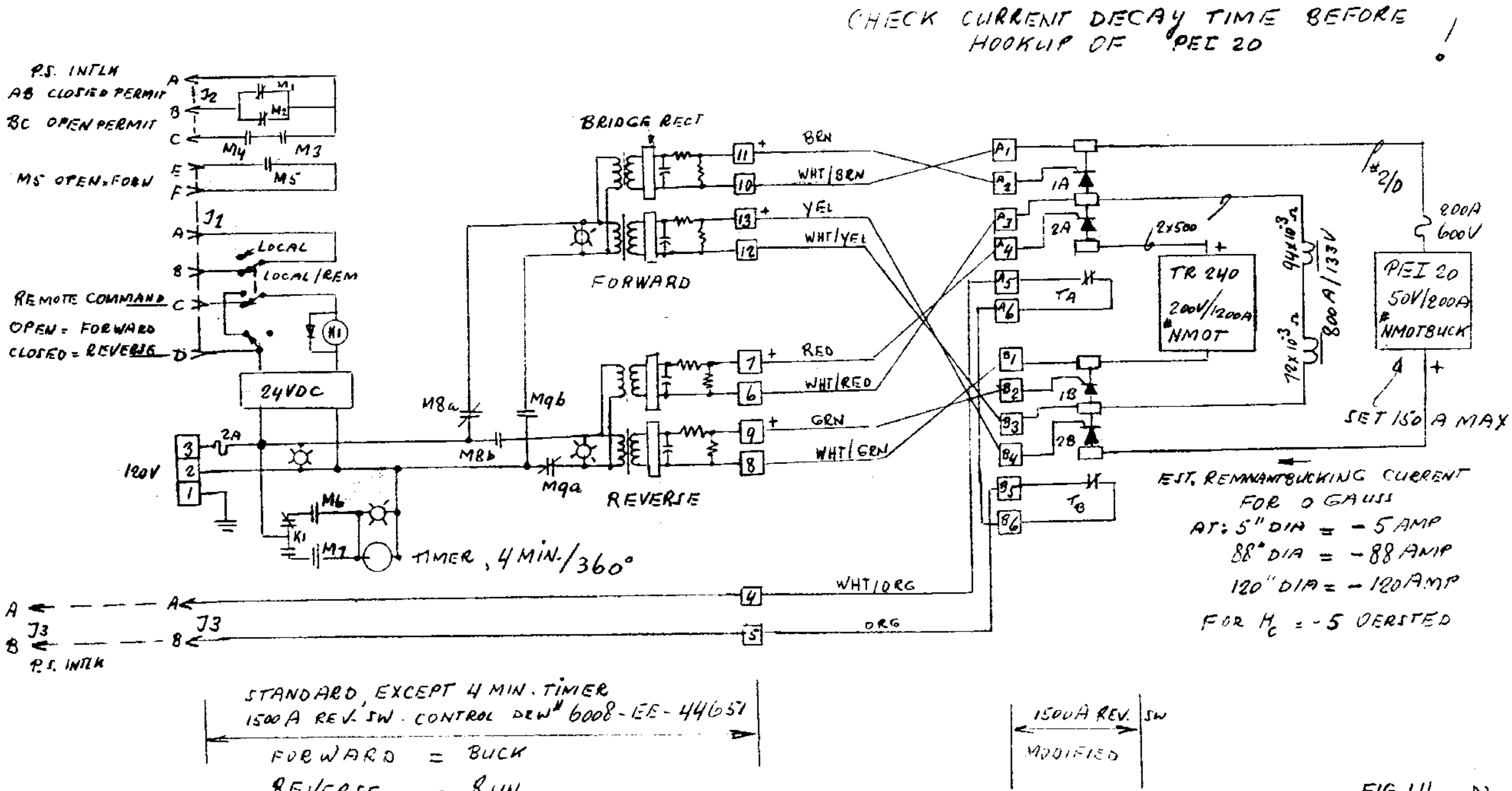

FIG 14

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE

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NAME: A T VISSER

DATE: 11/12/86

REVISION DATE:

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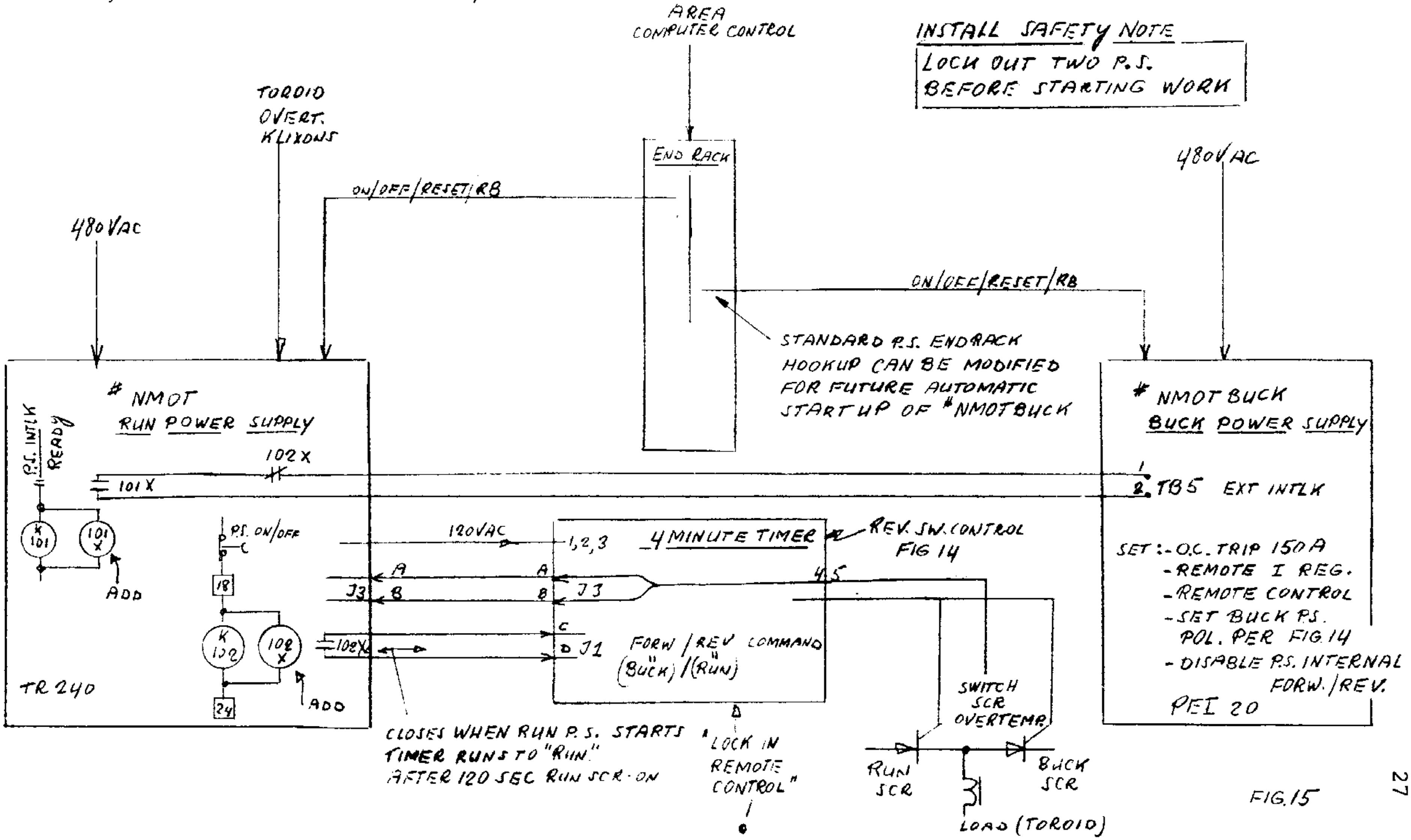

FIG. 15